Pulsar Kick — Anisotropy, Scattering, and Their Interplay

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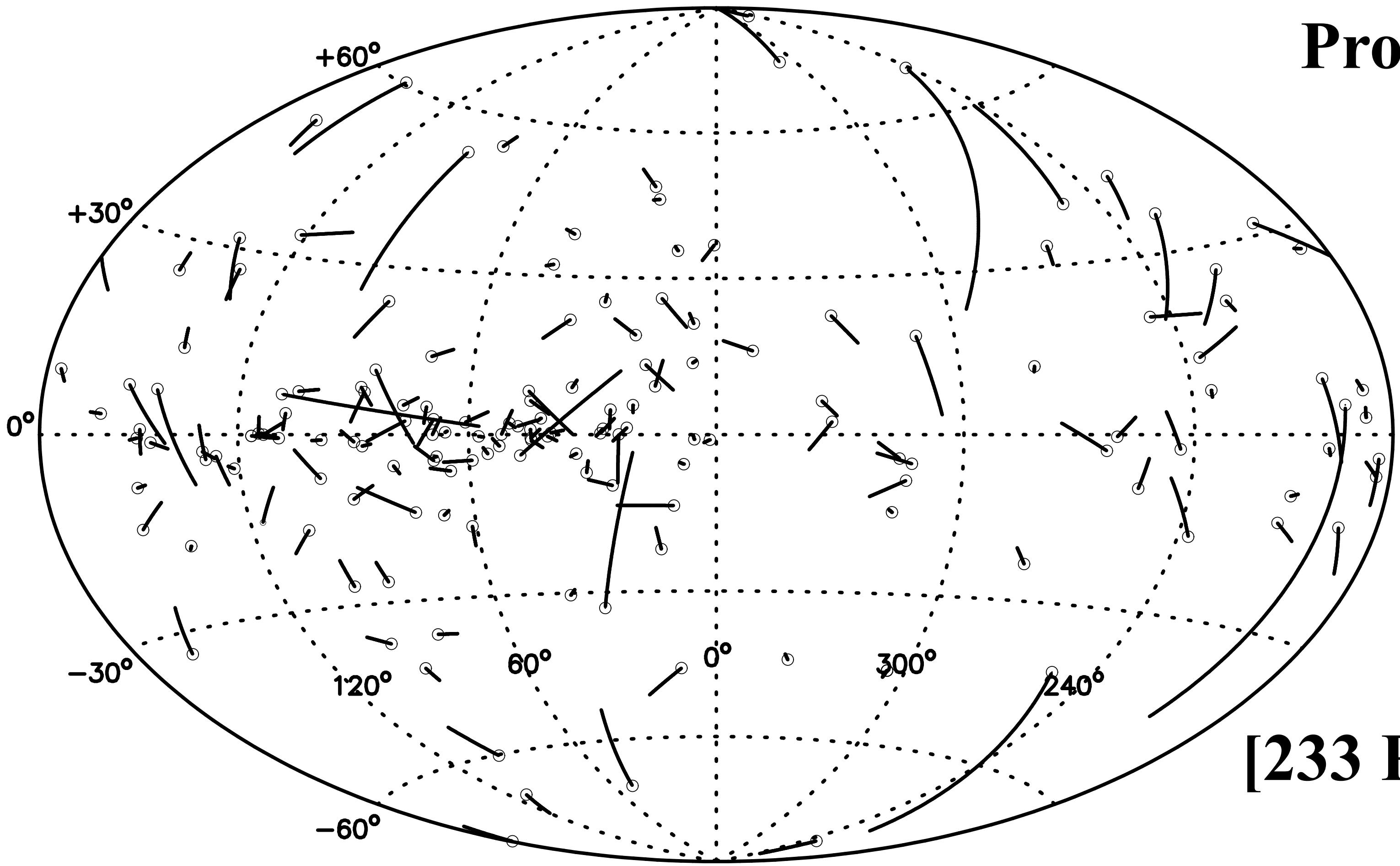
— Condensed Matter Physics of QCD @ YITP —

Pulsar Kick



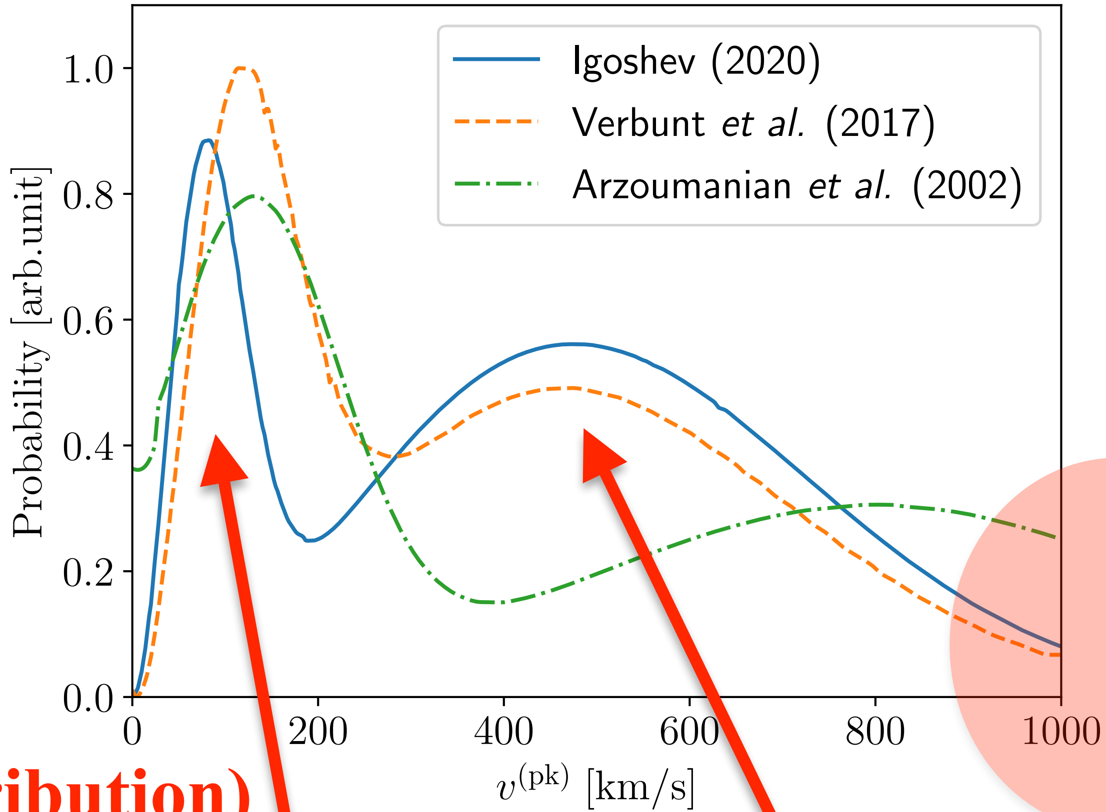
Proper motion
+
Distrance
=
Velocity

[233 Pulsars]

Hobbs-Lorimer-Lyne-Kramer (2005)

Pulsar Kick

From Chengpeng Yu's Doctoral Thesis



~ 15%
> 1000 km/s

Bimodal?
(mass distribution)

~ 100 km/s

~ 500 km/s

Pulsar Kick

Conventional (not interesting) scenario

Crab Nebula (Chandra)

Supernova is asymmetric → kick

Numerical simulation ~ 200 km/s

Fryer (2004)

NEUTRON STAR KICKS FROM ASYMMETRIC COLLAPSE

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ABSTRACT

Many neutron stars are observed to be moving with spatial velocities, in excess of 500 km s^{-1}. A number of mechanisms have been proposed to give neutron stars these high velocities. One of the leading classes of models proposed invokes asymmetries in the core of a massive star just prior to collapse. These asymmetries grow during the collapse, causing the resultant supernova to be also asymmetric. As the ejecta is launched, it pushes off (or "kicks") the newly formed neutron star. This Letter presents the first three-dimensional supernova simulations of this process. The ejecta is not the only matter that kicks the newly formed neutron star. Neutrinos also carry away momentum and the asymmetric collapse also leads to asymmetries in the neutrinos. However, the neutrino asymmetries tend to damp out the neutron star motions, and even the most extreme asymmetric collapses presented here do not produce final neutron star velocities above 200 km s^{-1}.

Neutrino-driven Scenarios

Anomalous hydrodynamics

Parity violating scattering / absorption

Strengthen this…

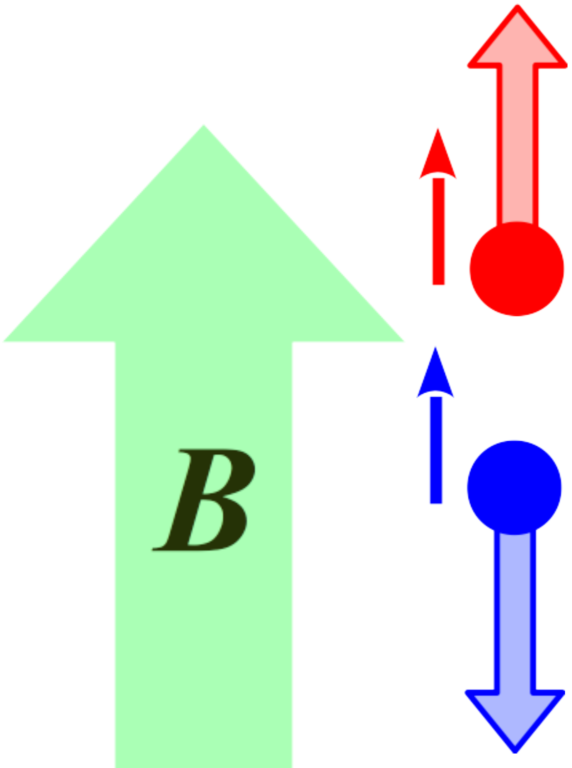
Neutrino beaming with CFL vortices (Blaschke *et al*. 2018)

Neutrino emission from CFL+*B* (Sagert and Schaffner-Bielich 2018)

Color-superconducting gap affects the neutrino mean free path in a dense medium ← QCD phases could be probed.

Topological Currents

Neutrino transport is even more affected by…



Right-handed: spin parallel to momentum

Left-handed: spin antiparallel to momentum

Chiral Magnetic Effect

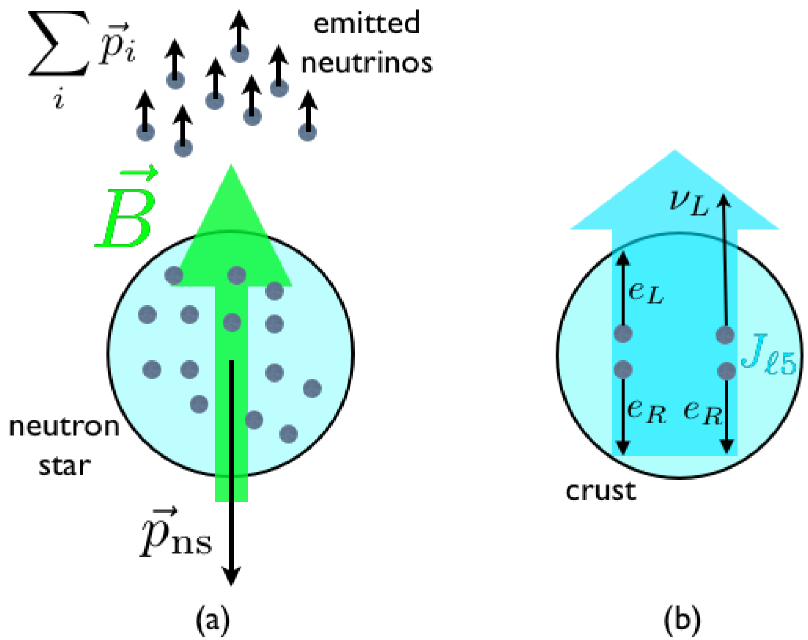
$$\boldsymbol{j} = \frac{e^2 \mu_5}{2\pi^2} \boldsymbol{B}$$

Chiral Separation Effect

$$\boldsymbol{j}_5 = \frac{e^2 \mu}{2\pi^2} \boldsymbol{B}$$

Topological Currents

One may think…



In anomalous hydrodynamics axial current is induced by *B* + (lepton) density.

Only left-handed neutrinos take a momentum away, giving a recoil to kick.

Kaminski-Uhlemann-Bleicher-Schaffner-Bielich (2014)
c.f. Yamamoto-Yang (2021) [Energy-momentum tensor]

Hydro regime is achieved by scatterings…
Any contribution from scattering already?

Parity Violating Scattering

Neutrino — Nucleon Scattering (Arras-Lai 1998)

$$|M_{ss'}(\mathbf{\Omega},\mathbf{\Omega}')|^2=\frac{1}{2}G_F^2c_V^2\{(1+3\lambda^2)+(1-\lambda^2)\mathbf{\Omega}\cdot\mathbf{\Omega}'$$

$\lambda=c_A/c_V$

$c_V=-1/2$

$c_A=-1.23/2$

$$+2\lambda(\lambda+1)\boxed{(s\mathbf{\Omega}+s'\mathbf{\Omega}')\cdot\hat{\mathbf{B}}}-2\lambda(\lambda-1)$$

$$\times\boxed{(s\mathbf{\Omega}'+s'\mathbf{\Omega})\cdot\hat{\mathbf{B}}}+ss'[(1-\lambda^2)$$

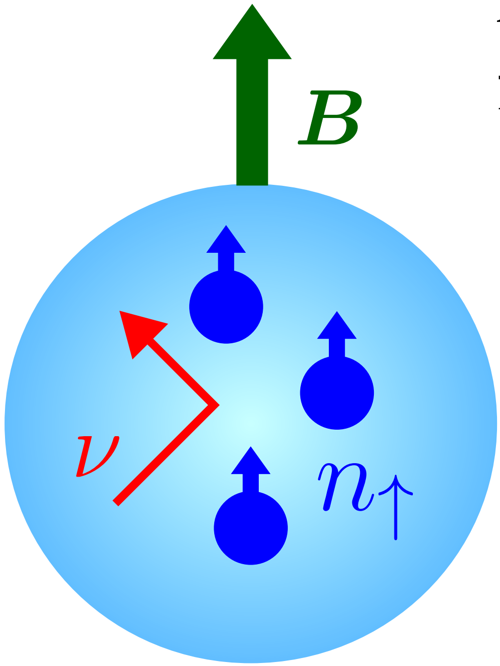
$$\times(1+\mathbf{\Omega}\cdot\mathbf{\Omega}')+4\lambda^2\mathbf{\Omega}\cdot\hat{\mathbf{B}}\mathbf{\Omega}'\cdot\hat{\mathbf{B}}]\} \qquad (4.2)$$

s, s' : *Nucleon* spin projection in the *B* axis

$\mathbf{\Omega}, \mathbf{\Omega}'$: *Neutrino* momentum direction

Absorption is important in the mechanism (skipped here).

Parity Violating Scattering



Asymmetry is quantified by replacement of from $(\boldsymbol{\Omega}, \boldsymbol{\Omega}')$ to $(-\boldsymbol{\Omega}', -\boldsymbol{\Omega})$:

$$2\lambda(\lambda+1)(s\boldsymbol{\Omega}+s'\boldsymbol{\Omega}')\cdot\hat{\mathbf{B}}-2\lambda(\lambda-1)(s\boldsymbol{\Omega}'+s'\boldsymbol{\Omega})\cdot\hat{\mathbf{B}}$$

$$2\lambda^2(s-s')(\boldsymbol{\Omega}-\boldsymbol{\Omega}')$$

Asymmetry should occur only when the nucleon spin is flipped: $s' = -s$

Remember Wu's experiment (${}^{60}_{27}\mathrm{Co} \to {}^{60}_{28}\mathrm{Ni} + e^- + \bar{\nu}_e + 2\gamma$) or ($d \to u + e^- + \bar{\nu}_e$) under $\boldsymbol{B}$.

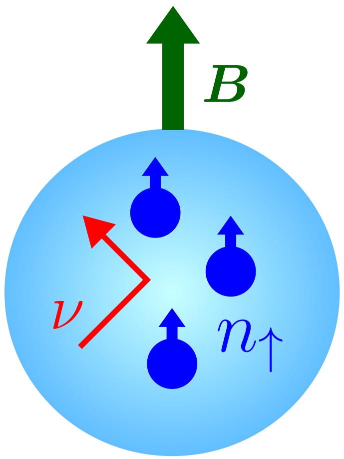
Chiral Anisotropy Conversion

$\boldsymbol{B}$ + Density = Axial Current

Chiral Separation Effect

$$j_5 = \frac{e}{2\pi^2}\mu \boldsymbol{B}$$

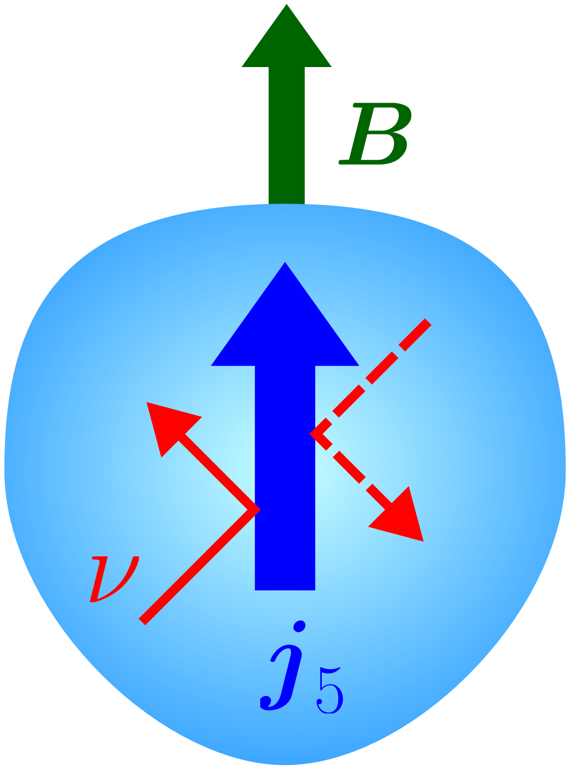
This expression represents polarized electrons under $\boldsymbol{B}$.



It is a tempting idea to consider scattering between the background current and the neutrinos.

The current has small energy/momentum which suppresses absorption.
→ Only scattering is relevant.

Chiral Anisotropy Conversion

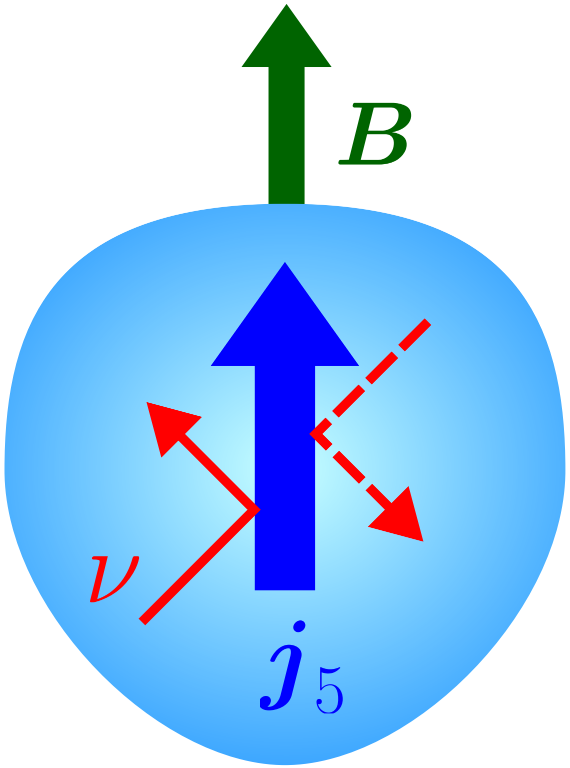


Fukushima-Yu (2024)

Axial Current + ν
= Symmetric Scattering
(No spin flip)

Axial Current + ν
+ Momentum Anisotropy
= Anisotropic Scattering
(Kick Acceleration)

Chiral Anisotropy Conversion



Fukushima-Yu (2024)

$$j_5 = \frac{e}{2\pi^2}\mu \boldsymbol{B}$$

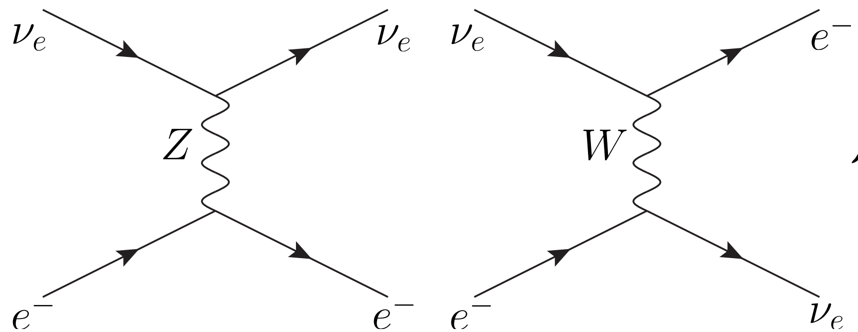
May have Fourier components…

In momentum space:

$$\tilde{j}_{5,e}(\boldsymbol{k}) = \tilde{j}_{5,e}(k)\bigl(1 + \alpha_1 \cos\theta + \cdots\bigr)$$

From the literature of numerical simulations, this asymmetry parameter is 0 ~ 0.3

Chiral Anisotropy Conversion



$$\mathcal{L}_{\text{eff}} = \frac{3G_F}{2\sqrt{2}} (j_{5,e})_\mu \bar{\nu}_e \gamma^\mu (1-\gamma_5)\nu_e$$

Effective interaction between background axial current and neutrinos (from NC and CC both).

$$\boldsymbol{a}(t) = -\frac{9G_F^2}{64\pi^4 M R(t)^2} \int d\Omega_1 d\Omega_2 dE E^2$$

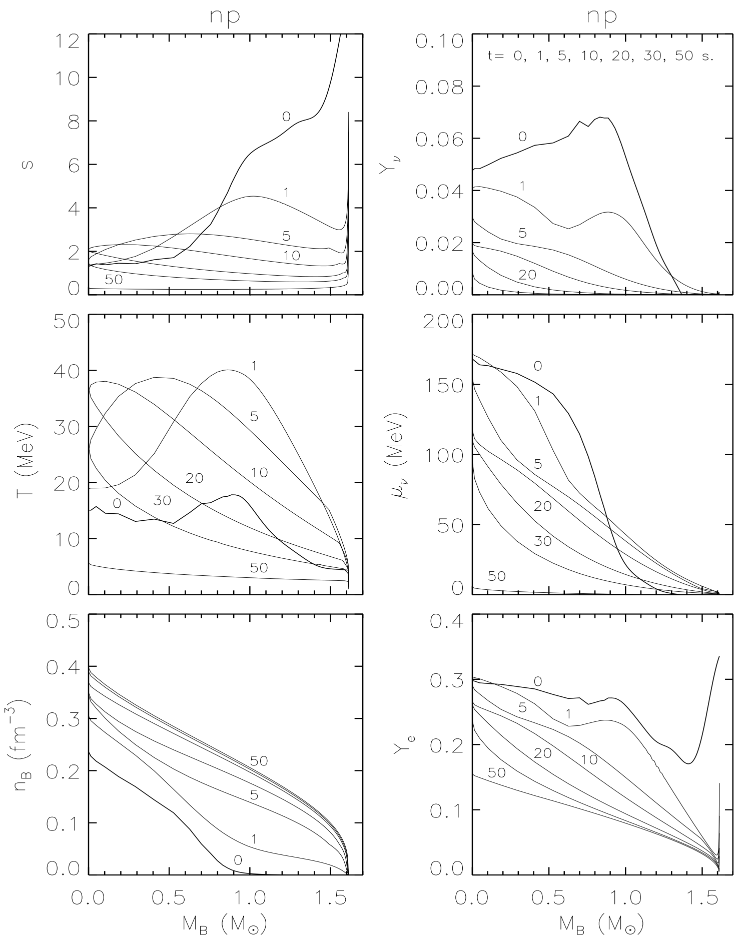
$$\times \left[1 + \cos\theta_1 \cos\theta_2 - \sin\theta_1 \sin\theta_2 \cos(\varphi_1 - \varphi_2)\right]$$

$$\times (\boldsymbol{k}_2 - \boldsymbol{k}_1) \, |\tilde{j}^z_{5,e}(\boldsymbol{k}_2 - \boldsymbol{k}_1, t)|^2 \, \underline{\frac{dL(t)}{dE}}$$

Neutrino number luminosity

Numerical Evaluation

We took the time evolution of proto-neutron star from Pons-Reddy-Prakash-Lattimer-Miralles (1998)

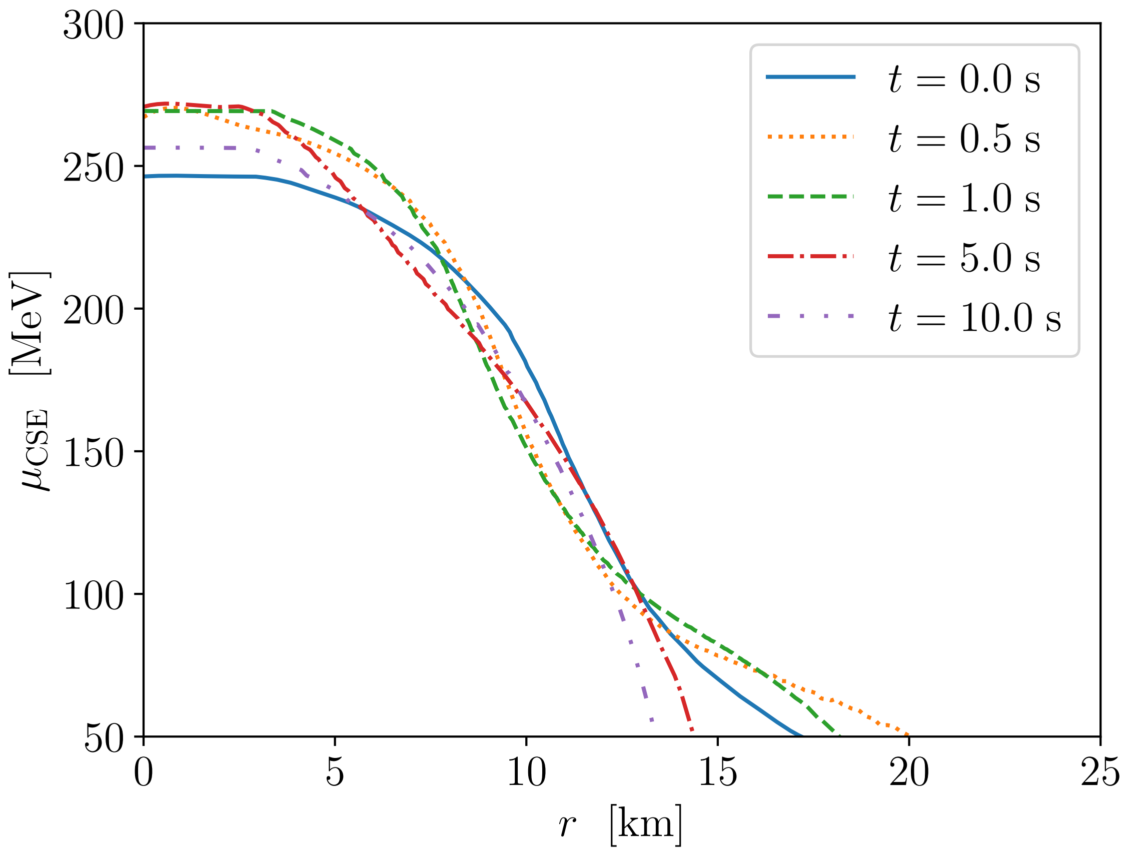


As a function of time and M_B that represents r for convenience, all the physical quantites are given.

Simulation should be updated with coupling to background current (and anomalous transport) — future work!

Numerical Evaluation

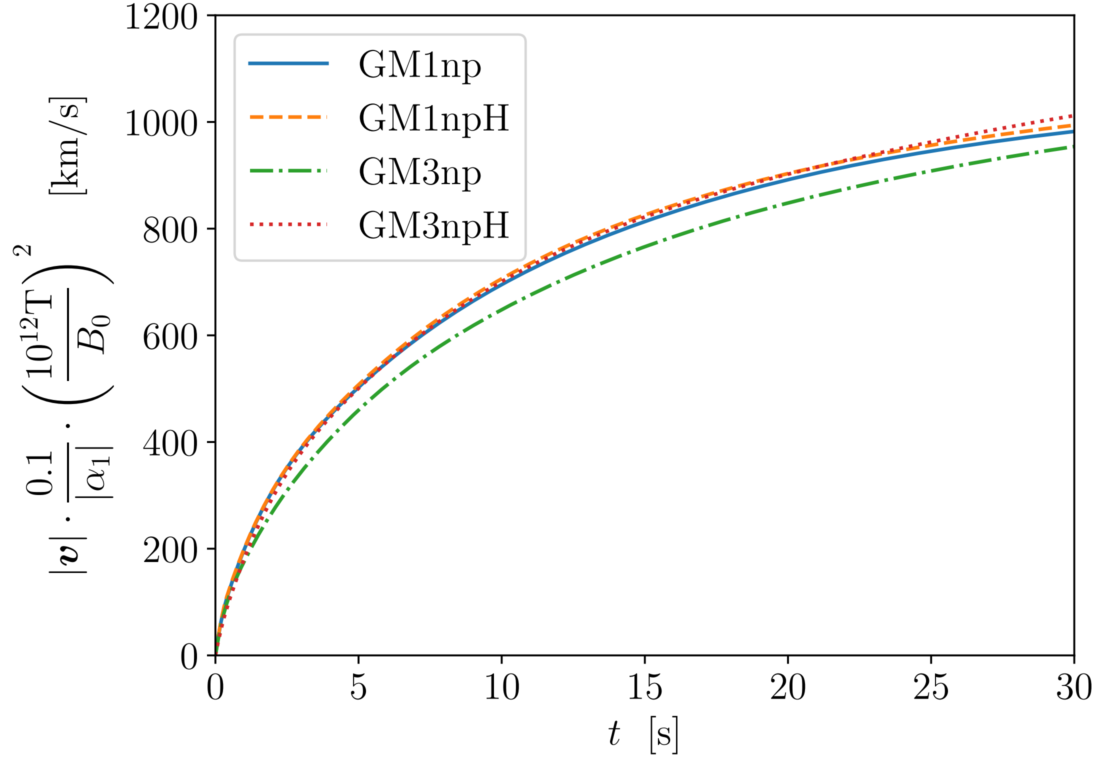
Time evolution and spatial distribution of density profile.
Now, $B = 10^{12}$T, is assumed to be constant in space/time.
This profile is translated to the distribution of the current.



Fukushima-Yu (2024)

Numerical Evaluation

Final velocity for several models (discussed in Pons *et al.*)



Fukushima-Yu (2024)

This is certainly one major mechanism among others!

$$|v_{\text{kick}}| \approx \frac{|\alpha_1|}{0.1}\left(\frac{B_0}{10^{12}T}\right)^2 \times 1000\text{km/s}$$

Conclusions

- Pulsar kick is not yet fully understood — maybe, multiple mechanisms compete/cooperate.

- So far, anisotropy / chiral effect are separately discussed as independent scenarios.

- Their interplay leads to an additional effect which turns out to be comparable to others — efficient conversion mechanism from anisotropy to kicks!